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On the Trouton–Noble Experiment

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The experiment of F. T. Trouton and H. R. Noble to detect the motion of the earth through the ether by means of electromagnetic torque on a charged, suspended, parallel-plate capacitor is reexamined. No previous explanation of the null result appears to be satisfactory because, as is shown herein, conventional relativistic electrodynamics predicts that the total electromagnetic field energy of the capacitor is different in the two orientations. Therefore, this combination predicts that the result should *not* be null. A new explanation of the null result is offered, based on a new equation for the energy density dU/dV in the electric **E** and magnetic **H** fields of a classical macroscopic charged body with a uniform speed β in units of the speed of light. This new equation $dU/dV=(E^2-H^2)/8\pi(1-\beta^2)$, in Gaussian units *in vacuo*, predicts that the total electromagnetic field energy of the capacitor is independent of its orientation in agreement with the null result of Trouton and Noble.

INTRODUCTION

In 1902, Trouton[1] proposed an experiment to detect the motion of the earth through the ether. His original reasoning was as follows. When a charged parallel-plate capacitor has a velocity $\boldsymbol{\beta}$ parallel to its plates as in Fig. 1, a uniform magnetic field $H=\beta E\sin\theta=\beta E$ exists throughout the volume V between the plates. (The velocity $\boldsymbol{\beta}$ is in units of the speed of light c and is with respect to the ether. The symbol E represents the electric field between the plates, and θ is the angle between $\boldsymbol{\beta}$ and **E**. Gaussian units are used, and the volume V is assumed to be a vacuum.) Using the conventional electromagnetic field energy equation

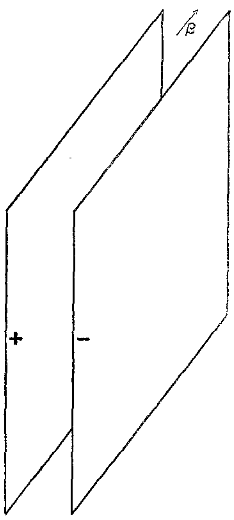


FIG. 1. When a charged parallel-plate capacitor is moving in a direction parallel to its plates, a uniform magnetic field $H=\beta E$ is produced between the plates.

$$U=\int_V \frac{E^2+H^2}{8\pi}\,dV=U_E+U_H, \qquad (1)$$

Trouton computed the total electromagnetic field energy U of the capacitor with $\boldsymbol{\beta}$ *parallel* to the plates to be

$$U_{\text{Plates}\parallel\beta}=[(E^2+\beta^2E^2)/8\pi]V$$
$$=(1+\beta^2)(E^2/8\pi)V$$
$$=(1+\beta^2)U_E. \qquad (2)$$

However, when $\boldsymbol{\beta}$ is *perpendicular* to the plates, the magnetic field between the plates is

$$H=\beta E\sin\theta=0.$$

Hence, the total electromagnetic field energy is, according to Eq. (1),

$$U_{\text{Plates}\perp\beta}=U_E. \qquad (3)$$

Thus, Trouton concluded that a freely suspended capacitor near the earth's surface (hence moving with the earth through the ether) should tend to turn so as to convert this extra field energy in the plate-parallel orientation to kinetic energy of rotation; i.e., the capacitor should tend to orient itself with its plates *perpendicular* to $\boldsymbol{\beta}$. Trouton did not utilize the concept of the Lorentz–Fitzgerald contraction or the transformation properties of the fields.

The theory of relativity does not change the qualitative substance of Trouton's arguments. In

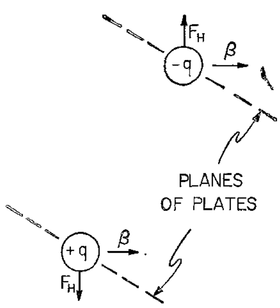
[1] F. T. Trouton, Sci. Trans. Roy. Dublin Soc. **7**, 379 (1902).

relativistic electrodynamics, it is customary[2–4] to identify the electromagnetic field energy of a moving charged body with the volume integral of the time component of the electromagnetic energy-momentum 4-tensor or

$$U=\int_V T_{44}dV=\int_V \frac{E^2+H^2}{8\pi}dV,$$

where **E** and **H** are the fields as measured for the moving body by a stationary laboratory observer (or are the fields as measured in the rest frame of the body and transformed to the laboratory frame by means of a Lorentz transformation). In essence, as far as electromagnetic field energy is concerned, the only changes needed to bring Trouton's arguments into agreement with conventional relativistic electrodynamics are to substitute the word *laboratory* for *ether* and to apply a Lorentz transformation to the pertinent field and volume quantities.

FIG. 2. Two point charges at opposite locations on the two capacitor plates. Each point charge moves in the magnetic field of the other and hence experiences a magnetic force as illustrated. These forces amount to a torque couple which tends to align the plates with $\boldsymbol{\beta}$.



The argument for the turning tendency as given in modern textbooks[5,6] is based upon torque rather than field energy. This argument, first stated by Searle,[7] is as follows. We consider the forces on a pair of point charges $+q$ and $-q$ in mirror-image positions on the capacitor plates as illustrated in Fig. 2. Each point charge, moving in the magnetic field of the other, experiences a magnetic force $\mathbf{F}_H$. These two forces, although equal and opposite, are not directed along the same line in space; hence, they appear to constitute a couple that tends to turn the capacitor so that its plates are *parallel* to the velocity.

Trouton performed the experiment with the collaboration of Noble. They observed no tendency of the capacitor to rotate.[8] This null result was confirmed by Tomaschek[9] in 1925 and reconfirmed by Chase[10] in 1926.

I. TROUTON'S ARGUMENTS IN TERMS OF CONVENTIONAL RELATIVISTIC ELECTRODYNAMICS

Except for Trouton's original arguments and a brief remark by Lorentz[11] in 1904, I am unaware of any discussion in the literature of the total electromagnetic energies of the capacitor in the two orientations. As shown below, conventional relativistic electrodynamics predicts the same qualitative result as Trouton, i.e., that the result should *not* be null. Therefore, it appears that no previous explanation of the Trouton–Noble result is satisfactory because no previous explanation has refuted Trouton's original arguments based on field energy.

We now apply the standard transformation equations for length and electromagnetic fields,

$$\ell_{||}=\ell_{0||}(1-\beta_c^2)^{1/2}, \qquad \ell_\perp=\ell_{0\perp}, \tag{4}$$

$$\mathbf{E}_{||}=\mathbf{E}_{0||}, \qquad \mathbf{E}_\perp=\frac{\mathbf{E}_{0\perp}+\boldsymbol{\beta}_c\times\mathbf{H}_0}{(1-\beta_c^2)^{1/2}}, \tag{5}$$

$$\mathbf{H}_{||}=\mathbf{H}_{0||}, \quad \text{and} \qquad \mathbf{H}_\perp=\frac{\mathbf{H}_{0\perp}-\boldsymbol{\beta}_c\times\mathbf{E}_0}{(1-\beta_c^2)^{1/2}}, \tag{6}$$

to Trouton's arguments.

Equations (4)–(6) transform a quantity measured in the rest frame of the capacitor and indicated by a subscript zero to the basic coordinate system (in this case, a frame based on the galaxy and indicated by no subscript). The velocity $\boldsymbol{\beta}_c$ is the velocity of the basic reference frame with

[2] W. K. H. Panofsky and M. Phillips, *Classical Electricity and Magnetism* (Addison–Wesley Publ. Co., Inc., Reading, Mass., 1962), 2nd ed., p. 382.

[3] J. D. Jackson, *Classical Electrodynamics* (John Wiley & Sons, Inc., New York, 1962), pp. 590–591.

[4] R. Becker and F. Sauter, *Electromagnetic Fields and Interactions* (Blaisdell Publ. Co., New York, 1964), Vol. 1, p. 395.

[5] W. K. H. Panofsky and M. Phillips, Ref. 2, pp. 274 and 349.

[6] R. Becker and F. Sauter, Ref. 4, pp. 397–401.

[7] G. F. C. Searle, Phil. Trans. Roy. Soc. London **A187**, 708 (1896).

[8] F. T. Trouton and H. R. Noble, Phil. Trans. Roy. Soc. London **A202**, 165 (1903).

[9] R. Tomaschek, Ann. Physik. **78**, 743 (1925); **80**, 509 (1926).

[10] C. T. Chase, Phys. Rev. **28**, 378 (1926).

[11] H. A. Lorentz, Proc. Acad. Sci. Amsterdam **6**, 809 (1904).

respect to the rest frame of the capacitor. If $\boldsymbol{\beta}$ represents the velocity of the capacitor with respect to the basic reference frame, then $\boldsymbol{\beta}_c$ is equal to $-\boldsymbol{\beta}$. The subscripts $\|$ and $\perp$ refer to the vector components parallel and perpendicular, respectively, to $\boldsymbol{\beta}_c$.

Because of Eqs. (4) the volume inside the moving capacitor is

$$V=V_0(1-\beta^2)^{1/2}. \quad (7)$$

Of course, $H_{0\|}$ and $H_{0\perp}$ (the magnetic-field components as measured in the rest frame) are zero; so, for our charged capacitor, Eqs. (5) and (6) reduce to the following:

$$\mathbf{E}_{\|}=\mathbf{E}_{0\|}, \qquad \mathbf{E}_{\perp}=\mathbf{E}_{0\perp}/(1-\beta^2)^{1/2}, \quad (8)$$

$$\mathbf{H}_{\|}=\mathbf{O}, \quad \text{and} \quad \mathbf{H}_{\perp}=(\boldsymbol{\beta}\times\mathbf{E}_0)/(1-\beta^2)^{1/2}. \quad (9)$$

These field values may be determined more simply by intuitive considerations based on the Lorentz–FitzGerald contraction of the capacitor structure.

Utilizing Eqs. (1), (7), (8), and (9) when the capacitor plates are *parallel* to $\boldsymbol{\beta}$, we compute the total electromagnetic-field energy of the capacitor to be

$$U_{\text{Plates}\,\|\,\beta}=[(E_{\perp}^2+H_{\perp}^2)/8\pi]\,V$$
$$=\frac{E_0^2/(1-\beta^2)+\beta^2E_0^2/(1-\beta^2)}{8\pi}\times V_0(1-\beta^2)^{1/2}$$
$$=\frac{(1+\beta^2)E_0^2V_0}{(1-\beta^2)^{1/2}8\pi}=\frac{1+\beta^2}{(1-\beta^2)^{1/2}}U_0. \quad (10)$$

On the other hand, Eqs. (1), (7), (8), and (9) predict that, when the capacitor plates are *perpendicular* to $\boldsymbol{\beta}$, the total electromagnetic field energy is

$$U_{\text{Plates}\,\perp\,\beta}=[(E_{\|}^2+0)/8\pi]V$$
$$=(E_0^2/8\pi)V_0(1-\beta^2)^{1/2}=(1-\beta^2)^{1/2}U_0. \quad (11)$$

Thus, we see that the effect of the theory of relativity is to *enhance* Trouton's original arguments rather than to confute them. According to Eqs. (2) and (3), Trouton found a difference of β^2U_E (which, to order β^2, is about β^2U_0) between the capacitor-field energies in the two orientations, whereas according to Eqs. (10) and (11) the difference is, to order β^2, about $2\beta^2U_0$. Hence, Trouton's original argument still applies qualitatively: Since the total electromagnetic-field energy is *different* for the two orientations, the two orientations are not equally preferred.

Of course, the null result is in agreement with the *principle of relativity*, which predicts that the two orientations *are* equally preferred. A purpose of the present paper is to show that a null result is predicted if a modification is made in Eq. (1) when applied to a uniformly moving charged body.

II. DERIVATION OF A SUBSTITUTE ENERGY DENSITY EXPRESSION

Since the null result of the Trouton–Noble experiment is in agreement with the *principle of relativity*, it appears reasonable to assume that the electromagnetic field energy of a charged body obeys the mass–energy equivalence relationship

$$U=mc^2. \quad (12)$$

If that is the case, then the electromagnetic field energy of a charged body transforms from the rest frame to another inertial frame in the same way as ordinary mass or

$$dU=dU_0/(1-\beta^2)^{1/2}, \quad (13)$$

where dU_0 is the electrostatic field energy in a volume dV_0 or

$$dU_0=(E_0^2/8\pi)dV_0 \quad (14)$$

and where dU is the electromagnetic energy in a volume dV of the field of the moving body.

Since the quantity (E^2-H^2) is a Lorentz *invariant*, we may write

$$E^2-H^2=E_0^2-H_0^2=E_0^2, \quad (15)$$

because $H_0=0$.

Substituting Eqs. (14), (15), and the differential form of Eq. (7) into Eq. (13) we obtain

$$dU=\frac{dU_0}{(1-\beta^2)^{1/2}}=\frac{E_0^2dV_0}{8\pi(1-\beta^2)^{1/2}}$$
$$=\frac{E^2-H^2}{8\pi(1-\beta^2)^{1/2}}\frac{dV}{(1-\beta^2)^{1/2}}=\frac{(E^2-H^2)dV}{8\pi(1-\beta^2)}. \quad (16)$$

Hence, the total electromagnetic field energy of a uniformly moving charged body is

$$U=\int_V [(E^2-H^2)/8\pi(1-\beta^2)]dV. \quad (17)$$

III. DISCUSSION OF THE SUBSTITUTE EXPRESSION

The question of the proper expression to use for the electromagnetic field energy of a moving charged body and the question of whether the relativity mass–energy equivalence relationship [Eq. (12)] applies to the electromagnetic field energy of a moving charged body have been much discussed in the literature, mainly in connection with the electromagnetic mass of the classical electron. According to the usual treatment[12,13] the electromagnetic rest mass of the electron is computed to be

$$m_e=\tfrac{4}{3}(U_0/c^2).$$

However, as long ago as 1922, Fermi[14] made a relativistic application of Hamilton's principle to the classical model of the electron and concluded that the usual relativity mass–energy equivalence [Eq. (12)] applies to the electromagnetic field energy of charged bodies as well as to other kinds of energy. However, Fermi's papers were apparently unnoticed, and basically the same result was subsequently obtained independently by Wilson,[15] Kwal,[16] and Rohrlich.[17]

We now make a comparison between the most recent of these results[17] and Eq. (17). Although Rohrlich worked in a manifestly covariant formulation, he converted his equation to ordinary three-dimensional space. When his total field energy equation [*his* Eq. (17)] is corrected by the insertion of a c^2 term and written in terms of the electromagnetic fields and the ordinary volume element, it becomes

$$U=\int_V \frac{E^2+H^2}{8\pi(1-\beta^2)}dV-\int_V \frac{(\mathbf{E}\times\mathbf{H})\cdot\mathbf{v}}{4\pi c(1-\beta^2)}dV. \quad (18)$$

We now show that Rohrlich's equation for the total field energy of the electron can be simplified so that it has the same form as Eq. (17), derived for classical macroscopic bodies. To do so we utilize the electromagnetic field identity

$$\mathbf{H}\equiv\boldsymbol{\beta}\times\mathbf{E},$$

for a charged body moving with a uniform velocity $\boldsymbol{\beta}$, the vector identity

$$\mathbf{A}\times(\mathbf{B}\times\mathbf{C})\equiv\mathbf{B}(\mathbf{A}\cdot\mathbf{C})-\mathbf{C}(\mathbf{A}\cdot\mathbf{B}),$$

and the trigonometric identity

$$\sin^2\theta+\cos^2\theta\equiv1.$$

The $(\mathbf{E}\times\mathbf{H})$ vector becomes

$$\mathbf{E}\times\mathbf{H}\equiv\mathbf{E}\times(\boldsymbol{\beta}\times\mathbf{E})\equiv\boldsymbol{\beta}E^2-\mathbf{E}(\boldsymbol{\beta}\cdot\mathbf{E}),$$

and the product $(\mathbf{E}\times\mathbf{H})\cdot\mathbf{v}/c$ becomes

$$\begin{aligned}(\mathbf{E}\times\mathbf{H})\cdot\boldsymbol{\beta}&\equiv\beta^2E^2-(\boldsymbol{\beta}\cdot\mathbf{E})^2\\&\equiv\beta^2E^2(1-\cos^2\theta)\\&\equiv\beta^2E^2\sin^2\theta\equiv H^2.\end{aligned}$$

Therefore Eq. (18) may be written

$$\begin{aligned}U&=\int_V \frac{E^2+H^2}{8\pi(1-\beta^2)}dV-\int_V \frac{H^2}{4\pi(1-\beta^2)}dV\\&=\int_V \frac{E^2-H^2}{8\pi(1-\beta^2)}dV,\end{aligned}$$

which agrees with Eq. (17), *Q.E.D.*

Thus, we see that the effect of Rohrlich's correction term [the $\mathbf{E}\times\mathbf{H}$ term in Eq. (18)] is to change from positive to negative the sign of the magnetic contribution of the (E^2+H^2) term in Eq. (18) or (1).

IV. A NEW EXPLANATION BASED ON ENERGIES

In arriving at Eqs. (10) and (11), which predict a nonnull result, we used (a) the conventional field-energy equation, (b) the transformation equations of the theory of relativity, and (c) the electromagnetic-field equations. We now proceed to use (b) and (c) together with Eq. (17) to predict a null result for the Trouton–Noble experiment.

Equation (17) is based on (d) the conventional *electrostatic* field energy equation, (b) the transformation equations of the theory of relativity,

[12] W. K. H. Panofsky and M. Phillips, Ref. 2, pp. 382–383.

[13] R. Becker and F. Sauter, Ref. 4, pp. 274–279 and 394–397.

[14] E. Fermi, Physik Z. **23**, 340 (1922); Atti Accad. Nazl. Lincei **31**, 184, 306 (1922); Nuovo Cimento **25**, 159 (1923).

[15] W. Wilson, Proc. Phys. Soc. (London) **48**, 736 (1936).

[16] B. Kwal, J. Phys. Radium **10**, 103 (1949).

[17] F. Rohrlich, Am. J. Phys. **28**, 639 (1960).

and (e) the mass–energy equivalence equation $U=mc^2$ under the assumption that it applies to *all* forms of energy (including electromagnetic).

For an *arbitrary* orientation of the capacitor plates, the value of E^2 is, according to Eqs. (8),

$$E^2=E_{||}^2+E_\perp^2=[(E_0^2-\beta^2E_{0||}^2)/(1-\beta^2)], \quad (19)$$

and the value of H^2 is, according to Eqs. (9),

$$H^2=H_{||}^2+H_\perp^2=\beta^2E_{0\perp}^2/(1-\beta^2). \quad (20)$$

Combining Eqs. (19) and (20), we obtain

$$E^2-H^2=E_0^2. \quad (21)$$

Of course we could have arrived at Eq. (21) via a shortcut by utilizing the fact that E^2-H^2 is a Lorentz invariant.

Substituting Eqs. (7) and (21) into Eq. (17), we obtain

$$U=\int_V \frac{E_0^2}{8\pi(1-\beta^2)}\,dV_0(1-\beta^2)^{1/2}=\frac{U_0}{(1-\beta^2)^{1/2}}.$$

Thus, we see not only that the total electromagnetic energy is independent of orientation but also that the total electromagnetic energy has the proper value to be the fourth component of a 4-vector, whereas the *conventional* energy values [Eqs. (10) and (11)] not only are *dependent* upon orientation but also may *not* constitute the fourth component of a 4-vector.

V. AN EXPLANATION BASED ON FORCES

The previous section is essentially an updating of Trouton's *energy* arguments. The present section is essentially an updating of Searle's *force* arguments. Perhaps the force arguments are more appealing to the intuition than the energy arguments.

According to Heaviside,[18] the electric field **E** at a point P a distance **r** from a point charge q moving with a uniform velocity $\boldsymbol{\beta}$ is

$$\mathbf{E}=(q/r^3)[(1-\beta^2)/(1-\beta^2\sin^2\theta)^{3/2}]\mathbf{r},$$

where θ is the angle between **r** and $\boldsymbol{\beta}$. He also showed that the magnetic field at P is

$$\mathbf{H}=\boldsymbol{\beta}\times\mathbf{E}.$$

Searle[19] showed that the *distribution* of charge having the same external electromagnetic fields as Heaviside's *point* charge is that of the charge on a conducting oblate spheroid moving along its minor axis, which has a length equal to $(1-\beta^2)^{1/2}$ times a major axis. Searle showed that the charge distribution on such a moving shell is the same as that on a conducting shell of the *same shape* at rest. He further showed that such an oblate spheroid surface is an *electrodynamic* (or "convection") *equipotential surface*; i.e., the total (or net) electromagnetic force $\mathbf{F}_{EH}$ on an element of charge on such a surface is perpendicular to the surface.

Consider such a surface centered on $+q$ of Fig. 2, and let $-q$ lie on the surface. The electromagnetic forces on $-q$ are illustrated in Fig. 3. The attractive electric force $\mathbf{F}_E$ on $-q$ is directed along the radial line toward the instantaneous present position of $+q$. The magnetic force $\mathbf{F}_H$ on $-q$ is a generally repulsive force directed radially away from the line of motion of $+q$. The vector sum $\mathbf{F}_E+\mathbf{F}_H=\mathbf{F}_{EH}$ is perpendicular to the oblate spheroid equipotential surface on which $-q$ is located.

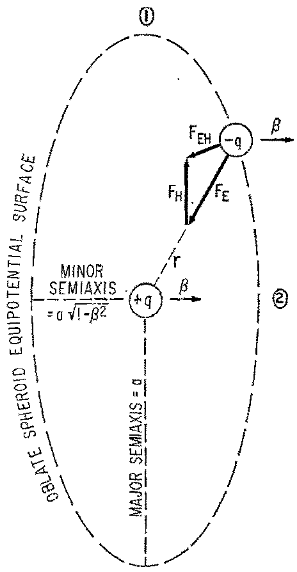


FIG. 3. The electrodynamic equipotential surfaces for a point charge $+q$ with a uniform velocity $\boldsymbol{\beta}$ are oblate spheroids with the minor axis [length equal to $(1-\beta^2)^{1/2}$ times a major axis] aligned with $\boldsymbol{\beta}$ and centered on $+q$. The locus of the point charge $-q$ separated from $+q$ by a Lorentz-rigid rod defines such a surface. The electric force $\mathbf{F}_E$ on $-q$ is directed along the radial line, and the magnetic force $\mathbf{F}_H$ is directed away from $\boldsymbol{\beta}$. The total electromagnetic force $\mathbf{F}_{EH}$ is perpendicular to the equipotential surface.

For any kind of steady-state equilibrium to be possible, we must provide some sort of rod to hold the charges apart. The best that we can do toward the goal of avoiding transfers of energy to and from the rod is to use a nonconducting Lorentz-rigid rod. (In the *capacitor* situation, we must perform an equivalent function; we must provide

[18] O. Heaviside, The Electrician **22**, 147 (1888).

[19] G. F. C. Searle, Phil. Trans. Roy. Soc. London A**187**, 675 (1896); Phil. Mag. **44**, 329 (1897).

some mechanical support to hold the plates apart.)

Such a rod compensates for $\mathbf{F}_E$ and for the component of $\mathbf{F}_H$ parallel to $\mathbf{r}$. Thus the net force on $-q$ is that component of $\mathbf{F}_H$ perpendicular to $\mathbf{r}$. This net force tends to rotate the rod or to place $-q$ so that $\mathbf{r}$ is perpendicular to $\boldsymbol{\beta}$. This is the torque couple discussed in connection with Fig. 2. For discussion purposes we may consider the mass of $+q$ to be so much greater than that of $-q$ that essentially only $-q$ tends to move relative to the center of mass of the system. Why does this force not tend to rotate the rod about $+q$?

The *formal* reason is that $-q$ is *constrained by the Lorentz-rigid rod to remain on an equipotential surface* with respect to $+q$. Since the surface is equipotential, there is no more reason for the charge $-q$ to accelerate spontaneously along this surface than there is for a stationary ball to start rolling spontaneously across a smooth level table.

The *intuitive* reason is that, if, for example, $-q$ moves along the spheroid surface toward point 1 in Fig. 3 as a result of the force $\mathbf{F}_H$, then $-q$ *becomes farther from* $+q$ because point 1 is on a *major* axis of the spheroid, whereas the $\boldsymbol{\beta}$ direction corresponds to the *minor* axis. Therefore the Lorentz–FitzGerald expansion of the rod as it moves toward point 1 *raises* the *electric* potential energy of $-q$ by *precisely* the *same* amount as the action of $\mathbf{F}_H$ *lowers* the *magnetic* potential energy.

In summary, the *magnetic* force on $-q$ tends to cause $-q$ to move toward point 1 on the spheroid, but the *electric* force on $-q$ tends to cause $-q$ to move toward point 2 on the spheroid because the electric force is attractive and point 2 is closer to $+q$. These two effects precisely cancel each other.

VI. SUMMARY

Trouton's original reasoning was that the total electromagnetic field energy of a moving parallel-plate capacitor is greatest when the plates are parallel to the velocity and least when the plates are perpendicular to the velocity. Hence, he concluded that such a freely suspended capacitor should rotate spontaneously so as to minimize its field energy; i.e., it should turn toward the transverse orientation.

When Trouton's argument is corrected to include the relativity transformations of the fields and capacitor structure, the qualitative predictions are the same: The total electromagnetic field energy is greatest in the plate-parallel orientation and is least in the plate-perpendicular orientation.

If, however, we abandon the conventional electromagnetic field energy equation

$$U=\int_V \frac{(E^2+H^2)dV}{8\pi},$$

as far as uniformly moving charged bodies are concerned and substitute for it a proposed new equation

$$U=\int_V \frac{(E^2-H^2)dV}{8\pi(1-\beta^2)},$$

the total electromagnetic field energy becomes independent of orientation, a prediction that is compatible with the null result of Trouton and Noble.

The new definition of electromagnetic field energy, Eq. (17), makes possible for the first time a satisfactory energy explanation of the Trouton–Noble experiment. Conversely, the Trouton–Noble result is, in one sense, an experimental verification of the proposed new definition of electromagnetic field energy for uniformly moving charged bodies. Alternatively, the Trouton–Noble result may be considered to be an experimental verification of the applicability of the mass–energy equivalence principle to electromagnetic energy.